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THE EFFECTS OF MULTIPLE REPAIRS ON INCONEL 718 WELD MECHANICAL PROPERTIES

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16. Abstract

Inconel 718 weldments were repaired 3, 6, 9, and 13 times using the gas tungsten arc welding process. The welded panels were machined into mechanical test specimens, postweld heat treated, and nondestructively inspected. Tensile properties and high-cycle fatigue life were evaluated and the results compared to unrepaired weld properties. Mechanical property data were analyzed using the statistical methods of difference in means for tensile properties and difference in log means and Weibull analysis for high-cycle fatigue properties.

Statistical analysis performed on the data did not show a significant decrease in tensile or high-cycle fatigue properties due to the repeated repairs. Some degradation was observed in all properties, however, it was minimal.

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THE EFFECTS OF MULTIPLE WELD REPAIRS ON INCONEL 718 WELD MECHANICAL PROPERTIES

I. INTRODUCTION

A. Background

Inconel 718 is a nickel-based, austenitic, precipitation-hardenable alloy, introduced by the Huntington Division of the International Nickel Co., in 1959. As with all superalloys, Inconel 718 has material property characteristics enabling high-temperature, high-strength design applications in corrosive environments, such as found in the space shuttle main engine (SSME). Inconel 718 is available in all material forms (wrought, cast, forged) and is readily weldable in both the annealed and age-hardened conditions [1,2].

The SSME is a reusable, high-performance, liquid-fueled rocket engine whose operating conditions necessitate the wide use of superalloys [3]. The engine is assembled with over 5,000 welded joints produced primarily with the gas tungsten arc (GTA) and electron beam (EB) welding processes. In spite of the complex nature of many of the weld joints, strict quality control requirements apply. The nondestructive inspection methods of dimensional (visual), radiographic, ultrasonic, and fluorescent dye-penetrant are required.

GTA welding is performed both manually and semiautomatically. Production acceptance rates for weld quality average 95 percent. This implies that 5 percent of the welded inches require repair at least once, and repeated repair attempts are not uncommon. In 1981, NASA/Marshall Space Flight Center (MSFC) conducted an experiment to determine if multiple repairs degraded the material properties of Inconel 718 [4]. GTA welds on 0.25- and 0.50-in wrought plates were repaired 13 times to determine if tensile or high-cycle fatigue properties were degraded. Tensile test results, for both longitudinal and transverse weld specimens, showed no degradation with multiple repairs. Fatigue tests were also conducted with longitudinal, all-weld-metal specimens. Again, the results showed no degradation in high-cycle fatigue life with multiple repairs. The test matrix did not include transverse weld specimens; therefore, the effects, if any, of multiple repairs on the weld heat affected zone (HAZ) were not evaluated.

B. Objective

The objective of this research was to reevaluate the effects of multiple repairs on Inconel 718 weldments. Tensile and high-cycle fatigue properties were again tested, this time including parent metal and HAZ, in addition to the weld fusion zone. Specimens were tested both with the weld bead flush machined (to eliminate geometry effects) and with the weld bead intact. Statistical analyses were used to determine, to a given statistical level of significance, any differences in properties between welds not repaired and those repeatedly repaired.

II. EXPERIMENTAL PROCEDURE

A. Population Selection

The effects of repairing on the physical and metallurgical properties of Inconel 718 were anticipated to increase linearly. Therefore, three, six, and nine repairs were selected to provide the data on repair effects. Mechanical property data for the control samples, in this case welds made without repairing, were available from previous programs conducted at MSFC and were not duplicated here [5,6]. The earlier program [5] examined the effects of 13 repairs on Inconel 718 so the mechanical property data for 13 repairs were also included on comparisons with three, six, and nine repairs. Bead profile measurements of the weld root were made of the welds with the bead left intact for accurate accountability of the actual conditions. A laser sensor system currently under development at MSFC was used for these measurements. A typical bead profile using the development sensor is shown in figure 1. All welds were made to meet the requirements for bead shape described in the Rocketdyne fusion welding specification RL10011 [7]. These requirements for 0.125-in material are: maximum weld width 0.440 in, maximum weld drop through 0.072 in, maximum weld height 0.072 in.

Most of the welds on the SSME are post-weld heat treated to the STA1 condition. This is a solution anneal and aging heat treatment developed jointly by Rocketdyne and NASA to provide adequate material properties. Welds are annealed at 1,900 °F for 30 min followed by an argon quench. Age hardening is obtained by heating to 1,400 °F for 10 h, furnace cooled to 1,200 °F, and held at 1,200 °F for a time period sufficient to have the aging cycle at both temperatures equal 20 h total.

The total population of test conditions is shown in table 1.

B. Repair Procedure

The Inconel 718 material used for this study was from one heat lot of material, 0.125-in thick stock. The material was procured to the aerospace materials specification (AMS) 5596D [8] with the chemical composition listed in table 2 and was in the 1,750 °F solution annealed condition prior to welding. Five sets of panels per repair group 4-x18-in long were welded together with an automatic GTA weld system. The weld system is interfaced to a computer providing accurate control of welding variables with a real-time printout of actual parameter values. The system enabled consistent repeatability of the weld setup throughout the program.

A square butt joint configuration was used. The panels were welded in the flat position, fixtured so that peaking of the welded panels would be minimized. The primary weld was made using a single pass, constant current arc with Inconel 718 cold filler wire addition. The primary weld parameters used are shown in table 3.

The panels were nondestructively inspected to meet class 1 weld acceptance criteria established in the Rocketdyne weld specification RL10011. The welded panels were then repaired using a procedure with the parameters shown in table 4. Rather than grinding out the weld and repairing with filler wire, it was decided to simulate a repair operation by applying an autogenous

weld pass that would remelt approximately 50 percent of the weld. This was done to expedite the repairing operation. Panels were repaired for 1-in lengths separated by 2-in increments as shown in figure 2. This sequence was selected so that stresses induced by surrounding cold metal on the repair solidification would be adequately duplicated. Three, six, nine, and 13 repairs were simulated in this manner. To validate the simulation method, a set of panels were also ground and repaired with filler wire three times.

All repaired welds were again inspected to class I requirements. Peaking and mismatch were also measured on the machined specimens. The mean value of peaking and mismatch measured for bead intact and flush machined three, six, and nine repaired specimens are shown in figures 3 and 4, respectively. Figure 3 shows a definite trend as the number of repairs increases. Peaking increases with increasing repairs and mismatch decreases. The increase in peaking would be expected as each repair pass induces additional thermal distortion of the panels. The test specimens that were flush machined follow the same trend for peaking and mismatch as the number of repairs increases as seen in figure 4. All measurements are within specification tolerances of 0.025 in for mismatch and 5° for peaking (per MSFC specification 560A [9]).

C. Evaluation Test Specimens

Weld-repaired areas were cut from the panels into mechanical test specimens of the configuration shown in figure 5 conforming to the guidelines established in the ASTM E8 [10] and ASTM E466 [11] specifications.

A student *t* analysis was used to compare the statistical means and statistical minimums of ultimate and yield strength properties for repaired and unrepaired welds. A student *t* analysis comparing difference in log means of high-cycle fatigue life for repaired and unrepaired welds at the two stress levels was also performed. Finally, a Weibull B1 life analysis was used to evaluate repaired versus unrepaired weld high-cycle fatigue lives at two stress levels.

III. RESULTS AND DISCUSSION

A. Metallographic Analysis

Cross sections were taken from each repair condition, three, six, and nine times, as well as an unrepaired weld to compare fusion zone and heat-affected zone metallographic structures. All samples were electrochemically etched in an oxalic acid solution. The as-welded macrostructures are shown in figures 6 through 8. The repair weld passes are seen to penetrate approximately 50 percent of the weld fusion zone. Higher magnification micrographs for the same weldments reveal minor differences in HAZ size and weld fusion zone solidification structures. The HAZ appears much wider at the root of the weld than at the face side. The dendritic spacing in the repaired portion of the fusion zone is much smaller than in the unrepaired fusion zone. This is expected with the lower heat input and associated smaller molten puddle. The width of the primary weld pass appears to increase as the number of repairs increases. One possible explanation of this is a shift in the Marangoni flow pattern within the molten weld pool during welding. The Marangoni flow is

outward toward the edge of the puddle for "pure" metals and is driven inward by contamination of the surface. Perhaps the repair weld heat passes clean the surface such that the weld surface is more "pure." The multiple repairing effects on the heat-affected zone grain growth region are eliminated in the subsequent postweld heat treatment as represented in figure 9.

Microstructures of the STA1 weldments at the equiaxed to dendritic transition at the weld fusion interface are shown in figures 10 through 13. Delta phase of Ni_3Nb precipitates are seen in the gamma double prime matrix, mostly at grain boundaries. The amount of delta phase in the unrepaired micrograph is much less than all three repair micrographs. Laves phase is observed within the delta phase, appearing white in the micrographs. Carbides are dispersed throughout the matrix and do not appear to be affected by repairing. Figure 14 shows the same area in the weld prior to postweld solution treating and aging.

B. Tensile Strength Analysis

Tensile tests were run using a Tinius Olsen (DS-30) servo-hydraulic tensile testing machine. Ultimate tensile strength, yield strength, elongation, and modulus were determined for three, six, and nine repairs, for specimens both with weld bead intact and weld bead flush machined, and for parent metal specimens. Tensile properties for unrepaired welds with the bead flush machined were available from a previous NASA program [6] using only 10 randomly selected data points to eliminate population size artifacts from the analysis. Average values for the above properties are listed in table 5. Bead-on tensile specimens all broke in the parent metal, away from the weld fusion zone and heat-affected zone. There appears to be no degradation in tensile properties as the number of repairs increases. Percent elongation increases slightly as number of repairs increases. Comparing the bead-on tensile properties to the parent metal control specimen tensile property results shows some degradation in properties due to welding even though both broke in the parent metal. This could be the result of peaking and mismatch induced during welding, although actual measured values were very small. Ductility, as measured by percent elongation, is greatly reduced for welded specimens compared to parent metal specimens.

The tensile properties for flush-machined weld specimens show an increase in average ultimate tensile and yield strength as the number of repairs increases. However, unrepaired welds had higher average ultimate and yield strength than three and six repairs, but lower than nine repairs. Percent elongation and stiffness appear to be unaffected by increasing repairs. The tensile test specimens with flush-machined weldments all failed in the weld fusion zone.

A student *t* statistical analysis was done to compare difference in means for ultimate and yield properties between repaired welds and unrepaired welds. Confidence levels of 90 percent or greater (95 and 99 percent) were used for the analysis to assure adequate conservatism in the analysis results. A summary of these results for flush-machined welds is listed in table 6. The student *t* analysis confirmed that unrepaired welds were higher in yield strength than three-times repaired welds for flush-machined welds. There was no discernable difference in means for yield strength between unrepaired and three-repairs (with grind and fill) and six-repairs flush-machined welds. The nine-times repaired flush-machined welds were greater in yield strength than an unrepaired weld.

The student t analysis for difference between unrepaired and repaired weld mean strengths for flush-machined welds followed the same trend as for yield strength. The ultimate tensile strength for nine repairs is greater than for unrepaired welds. The comparison of welds repaired three times with an autogenous heat pass to welds repaired three times by grinding and filling showed no discernable difference in means for ultimate strength and a slight increase in yield strength for the grind and fill repairs. This implies the autogeneous heat pass is a good simulation of a repair operation. Figure 15 also illustrates the minimal effect of multiple repairs on mean tensile and yield strengths. In fact, a decrease of 5 ksi on tensile strength relates to a 3-percent reduction in strength of an unrepaired weld.

The results of the student t analysis, comparing the difference in means between repaired welds with the weld bead left intact and parent metal specimens are listed in table 7. Parent metal samples had higher yield and tensile strengths than all repaired welds to a 99-percent confidence level. This is opposite to what is expected since repaired welds also failed in the parent metal, well away from the weld fusion zone and HAZ region of the weld. The reduction in tensile properties of the repaired welds, however, is small (approximately 1 percent of the parent metal properties). Comparison of the number of repaired bead-intact welds shows yield strength first dropping off, then improving as number of repairs increases. There is no discernible difference in means on ultimate strength except six repairs are better than nine repairs. Yield strength appears to improve with multiple repairs. Figure 16 graphically shows the effects of multiple repairs on mean tensile and yield strength for welds tested with the bead intact. Again, the amount of degradation on properties is insignificant.

C. Fatigue Property Analysis

High-cycle fatigue tests were conducted on all repair groups at two stress levels. Problems during testing resulted in scrapping a significant number of specimens so that fatigue curves could not be generated. High- and low-stress levels were selected so that specimens would fail after approximately 100,000 cycles and 1,000,000 cycles, respectively. The stress levels chosen were 110 ksi and 65 ksi. An R ratio (minimum stress divided by maximum stress) of 0.05 was selected to represent engine operating conditions. During testing, a load cell had to be replaced, and the new cell was not recalibrated. This discrepancy was not noticed until after all the six repairs, weld bead-on test specimens were tested. This was calculated to result in stress levels of 77 ksi and 131 ksi at an R ratio of 0.205. Therefore the data for the six repairs, bead-on high-cycle fatigue were dropped from the subsequent analyses. The tests were conducted on a Sontag servo-hydraulic fatigue tester cycling at 30 Hz. Unrepaired-weld, high-cycle fatigue data from a previous program were used as controls. However, these data, as well as weld high-cycle fatigue data for 13 repairs were generated on a 10K MTS servo-hydraulic fatigue tester cycling at 40 Hz. The high stress level was chosen as 100 ksi, the low stress level was 65 ksi, and the R ratio was 0.05.

All high-cycle fatigue specimens failed through the weld fusion zone for the flush-machined weld bead, and at the fusion boundary for the specimens with the weld bead left intact. Thus, multiple repairs do not affect the weld HAZ in that the position of failure did not change between welds repaired versus unrepaired flush machined, and between welds repaired versus unrepaired weld bead left intact.

A student *t* analyis was done comparing the difference in log means of the number of cycles to failure for the different repair groups at the two stress levels. The results of this analysis are summarized in table 8 for flush-machined welds and in table 9 for bead-intact welds. The flushed-weld data showed no discernible difference to a 90-percent confidence level for all groups compared. There was also no discernible difference in log means of cycles to failure between unrepaired welds and repaired welds for both stress levels. Also, there was no discernible difference in log means of welds receiving a simulated repair (heat pass) versus a grind and fill repair at the two stress levels tested. However, there is a difference in log means between repair groups with the weld bead left intact (table 9). To a 99-percent confidence level, welds repaired three times are better than welds repaired nine times at the two stress levels tested. This substantiates the previous program results comparing 13 repairs to unrepaired welds with the weld bead left intact. This implies that the degradation is due to an increase in the stress intensity factor, or a geometry effect. Inconel 718 is known to be notch sensitive [12] which correlates with the increase in weld bead height measured at the root of the weld as the number of repairs increases. Figure 17 shows the average bead height for the repaired welds measured from the weld face side and root side. A definite trend is observed as the number of repairs increases. The bead height on the weld face decreases with increasing repairs, and the drop through increases as the number of repairs increases. This could be related to the transient thermal compressive stresses induced in the material below the repair weld puddle extruding the weld metal out the bottom of the weld. This would imply that distortion of the welded panels would also increase due to the extrusion. This was verified previously in figure 7, which showed peaking to increase as the number of repairs increased.

A Weibull analysis was also done on all high-cycle fatigue data. A list of the beta values is given in table 10. The beta value, or slope of the line, indicates the failure mode of the population. Low values imply low time failures or scatter in the data. High beta values represent a "wearout" failure mode [13].

Figure 18 shows the plot of the L(10) life for each test condition with the weld beads flush machined. The L(10) life represents the number of cycles above which 90 percent of the population will fall. First, the unrepaired and 13-repaired plots have the same slope. But the three, six, and nine repairs have a different slope (approximately the same), implying the different weld parameters used between the two programs biased the results. Another possible cause might be the 10-Hz difference in cyclic frequency between the two fatigue testing machines used, however, a difference of 10 Hz certainly seems insignificant. The six- and nine-repair fatigue lives at 65 ksi are less than the 13 repaired. At the high stress level, the three-repair line crosses the unrepaired line, implying three repairs are better than none at high-stress levels. Nevertheless, at the low-stress level, the repaired welds failed approximately 200,000 cycles before the unrepaired welds.

Figure 19 shows the L(10) life for each test condition with the weld beads left intact. Again, different slopes are observed for the 13- and no-repair conditions compared to the three- and nine-repair conditions. A noticeable degradation in life is evident at both stress levels.

Fracture surfaces were analyzed with no conclusive results on failure initiation point trends. Most failures initiated at a corner, the most likely location of the highest stress intensity. There was no correlation in failure from the face or root side of the weld with cycles to failure. Figure 20 shows a fracture surface using scanning electron microscopy (SEM) of an unrepaired-weld high-cycle fatigue specimen tested at 100 ksi. Figure 21 shows a fracture surface of a weld repaired 13 times and high-cycle fatigue tested at 65 ksi. Secondary cracks can be found, but no higher order precipitates.

IV. CONCLUSIONS

1. Multiple repairs on Inconel 718 weldments do not affect the HAZ such that mechanical properties are altered.

2. Multiple repairs do not degrade tensile properties to a level of engineering significance.

3. High-cycle fatigue tests of flush-machined welds at high stress levels are not affected by repairs, but at low-stress levels the fatigue life is somewhat reduced as the number of repairs increases.

4. High-cycle fatigue tests of bead-intact welds exhibit reduced fatigue life as the number of repairs increases at both high- and low-stress levels.

5. The weld root bead height increases linearly as the number of repairs increases.

Table 1. Population of test conditions.

All conditions primary GTA welded and postweld heat treated after repairing to STA1 condition.

Bead On	Flush Machined
No repairs	No repairs
3 repairs	3 repairs
	3 repairs (grind and fill)
6 repairs	6 repairs
9 repairs	9 repairs
13 repairs	13 repairs

Table 2. Chemical composition of Inconel 718.

Ni	50.00 to 55.00 percent	Cr	17.00 to 21.00 percent
Nb, Ta	4.75 to 5.50 percent	Mo	2.80 to 3.30 percent
Ti	0.65 to 1.15 percent	Al	0.20 to 0.80 percent
C	0.08 percent maximum	B	0.006 percent maximum
Co	1.00 percent maximum	Mn	0.35 percent maximum
Si	0.35 percent maximum	Cu	0.30 percent maximum
P	0.015 percent maximum	S	0.015 percent maximum
Fe	Balance		

Table 3. Primary weld parameters.

Parameters	3,6,9 Repairs	13, No Repair*	No Repair**
Polarity	DCEN	DCEN	DCEN
Tungsten	2 percent Th	2 percent Th	2 percent Th
Elec. Conf.	30° angle	30° angle	30° angle
Shield/Flow	Ar/30 cfh	Ar/30 cfh	Ar/30 cfh
Back Purge/Flow	Ar/25 cfh	Ar/25 cfh	Ar/25 cfh
Filler Wire	0.045 in	0.045 in	0.045 in
Current	130 A	173 A	153 A
Voltage	8.6 V	7.0 V	7.5 V
Travel Speed	5 ipm	5 ipm	5 ipm
Wire Speed	25 ipm	15 ipm	15 ipm

*Welds made from previous program [5] fatigue properties.
**Welds made from previous program [6] tensile properties.

Table 4. Repair pass weld parameters.

Parameters	3,6,9 Repairs	13 Repairs*
Polarity	DCEN	DCEN
Tungsten	2 percent Th	2 percent Th
Elec. Conf.	30° Angle	30° Angle
Shield/Flow	Ar/30 cfh	Ar/30 cfh
Back Purge/Flow	Ar/25 cfh	Ar/25 cfh
Filler Wire	0.045 in	0.045 in
Current	100 A	140 A
Voltage	8.0 V	7.0 V
Travel Speed	5 ipm	5 ipm

*Welds made from previous program.

Table 5. Average tensile properties.

Number of Repairs	UTS (psi)	YS (psi)	Percent Elongation	Stiffness (Million) (psi)
3 Bead On	195,698	165,950	11.12	32.21
6 Bead On	196,571	166,265	13.0	31.37
9 Bead On	195,209	169,471	13.8	33.45
No Repair Flush	180,774	158,550	4.9	30.76
3 Flush	173,736	148,990	5.3	27.54
3 Flush and Grind	178,879	154,502	4.37	28.69
6 Flush	179,852	155,630	5.9	28.38
9 Flush	183,531	159,658	5.7	28.12
Parent Metal	199,303	171,195	21.1	28.93

Table 6. Student t analysis difference in means – flush machined welds.

Unrepaired Yield > 3 Repair Yield	99-percent Confidence
Unrepaired Yield = 3 Grind and Fill Yield	90-percent Confidence
Unrepaired Yield = 6 Repair Yield	90-percent Confidence
9 Repair Yield > Unrepaired Yield	90-percent Confidence
6 Repair Yield > 3 Repair Yield	99-percent Confidence
9 Repair Yield > 6 Repair Yield	99-percent Confidence
3 Grind and Fill Yield > 3 Repair Yield	95-percent Confidence
9 Repair Yield > 3 Repair Yield	99-percent Confidence
Unrepaired Ultimate > 3 Repair Ultimate	90-percent Confidence
Unrepaired Ultimate = 6 Repair Ultimate	90-percent Confidence
Unrepaired Ultimate = 3 Grind and Fill Ultimate	90-percent Confidence
9 Repair Ultimate > Unrepaired Ultimate	95-percent Confidence
6 Repair Ultimate > 3 Repair Ultimate	95-percent Confidence
9 Repair Ultimate > 6 Repair Ultimate	99-percent Confidence
9 Repair Ultimate > 3 Repair Ultimate	99-percent Confidence
3 Repair Ultimate = 3 Grind and Fill Ultimate	90-percent Confidence

Table 7. Student t analysis difference in means – bead intact welds.

Parent Metal Yield > 3 Repair Yield	99-percent Confidence
Parent Metal Yield > 6 Repair Yield	99-percent Confidence
Parent Metal Yield > 9 Repair Yield	95-percent Confidence
9 Repair Yield > 6 Repair Yield	95-percent Confidence
9 Repair Yield > 3 Repair Yield	95-percent Confidence
3 Repair Yield = 6 Repair Yield	90-percent Confidence
Parent Metal Ultimate > 3 Repair Ultimate	99-percent Confidence
Parent Metal Ultimate > 6 Repair Ultimate	99-percent Confidence
Parent Metal Ultimate > 9 Repair Ultimate	99-percent Confidence
3 Repair Ultimate = 6 Repair Ultimate	90-percent Confidence
3 Repair Ultimate = 9 Repair Ultimate	90-percent Confidence
6 Repair Ultimate > 9 Repair Ultimate	90-percent Confidence

Table 8. Student t analysis difference in log means – flush machined welds.

Unrepaired 65 ksi = 3 Repair 65 ksi	90-percent Confidence
Unrepaired 65 ksi = 6 Repair 65 ksi	90-percent Confidence
Unrepaired 65 ksi = 9 Repair 65 ksi	90-percent Confidence
Unrepaired 65 ksi = 13 Repair 65 ksi	90-percent Confidence
3 Repair 65 ksi = 6 Repair 65 ksi	90-percent Confidence
6 Repair 65 ksi = 9 Repair 65 ksi	90-percent Confidence
3 Repair 65 ksi = 9 Repair 65 ksi	90-percent Confidence
3 Repair 65 ksi = 3 Grind and Fill 65 ksi	90-percent Confidence
9 Repair 65 ksi = 13 Repair 65 ksi	90-percent Confidence
3 Repair 65 ksi = 13 Repair 65 ksi	90-percent Confidence
6 Repair 65 ksi = 13 Repair 65 ksi	90-percent Confidence
3 Repair 110 ksi = 6 Repair 110 ksi	90-percent Confidence
6 Repair 110 ksi = 9 Repair 110 ksi	90-percent Confidence
3 Repair 110 ksi = 9 Repair 110 ksi	90-percent Confidence
3 Repair 110 ksi = 3 Grind and Fill 110 ksi	90-percent Confidence

Table 9. Student t analysis difference in log means – bead intact welds.

3 Repairs 65 ksi > 9 Repairs 65 ksi	99-percent Confidence
Unrepaired 65 ksi > 3 Repairs 65 ksi	95-percent Confidence
Unrepaired 65 ksi > 9 Repairs 65 ksi	99-percent Confidence
Unrepaired 65 ksi > 13 Repairs 65 ksi	99-percent Confidence
3 Repairs 65 ksi > 13 Repairs 65 ksi	95-percent Confidence
9 Repairs 65 ksi = 13 Repairs 65 ksi	90-percent Confidence
3 Repairs 110 ksi > 9 Repairs 110 ksi	99-percent Confidence

Table 10. High cycle fatigue life beta values.

Test Condition	Beta
No Repairs Flush Machined at 65 ksi	2.9
3 Repairs Flush Machined at 65 ksi	2.9
3 Repairs (Grind and Fill) Flush at 65 ksi	1.65
6 Repairs Flush Machined at 65 ksi	2.63
9 Repairs Flush Machined at 65 ksi	3.95
13 Repairs Flush Machined at 65 ksi	3.15
No Repairs Flush Machined at 100 ksi	17.27
3 Repairs Flush Machined at 110 ksi	13.25
3 Repairs (Grind and Fill) Flush at 110 ksi	7.79
6 Repairs Flush Machined at 110 ksi	9.5
9 Repairs Flush Machined at 110 ksi	13.06
13 Repairs Flush Machined at 100 ksi	2.94
No Repairs Bead Intact at 65 ksi	2.14
3 Repairs Bead Intact at 65 ksi	2.12
9 Repairs Bead Intact at 65 ksi	4.27
No Repairs Bead Intact at 100 ksi	2.05
3 Repairs Bead Intact at 110 ksi	6.88
9 Repairs Bead Intact at 110 ksi	5.33
13 Repairs Bead Intact at 100 ksi	1.40

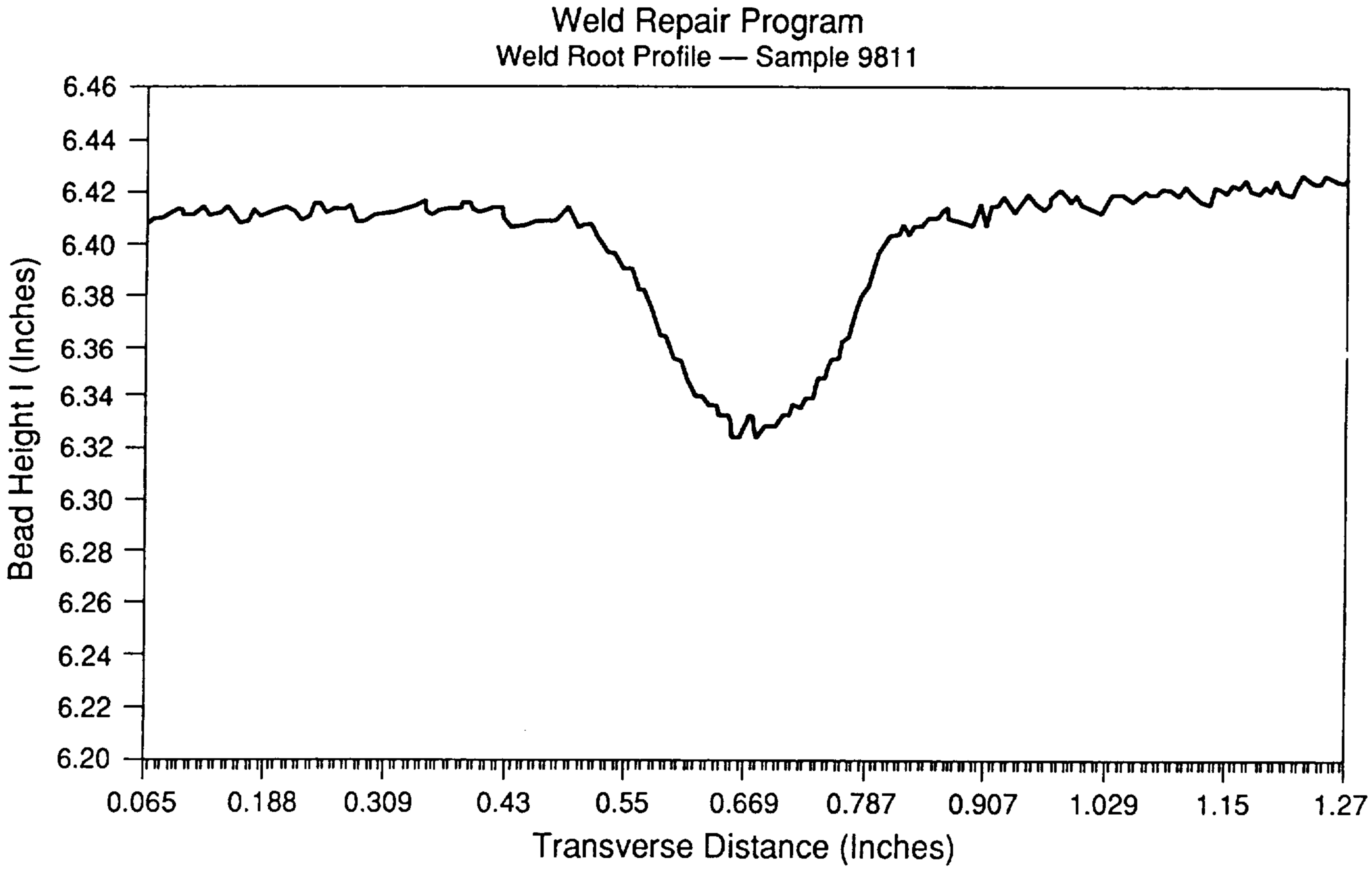


Figure 1. Weld bead profile measurement.

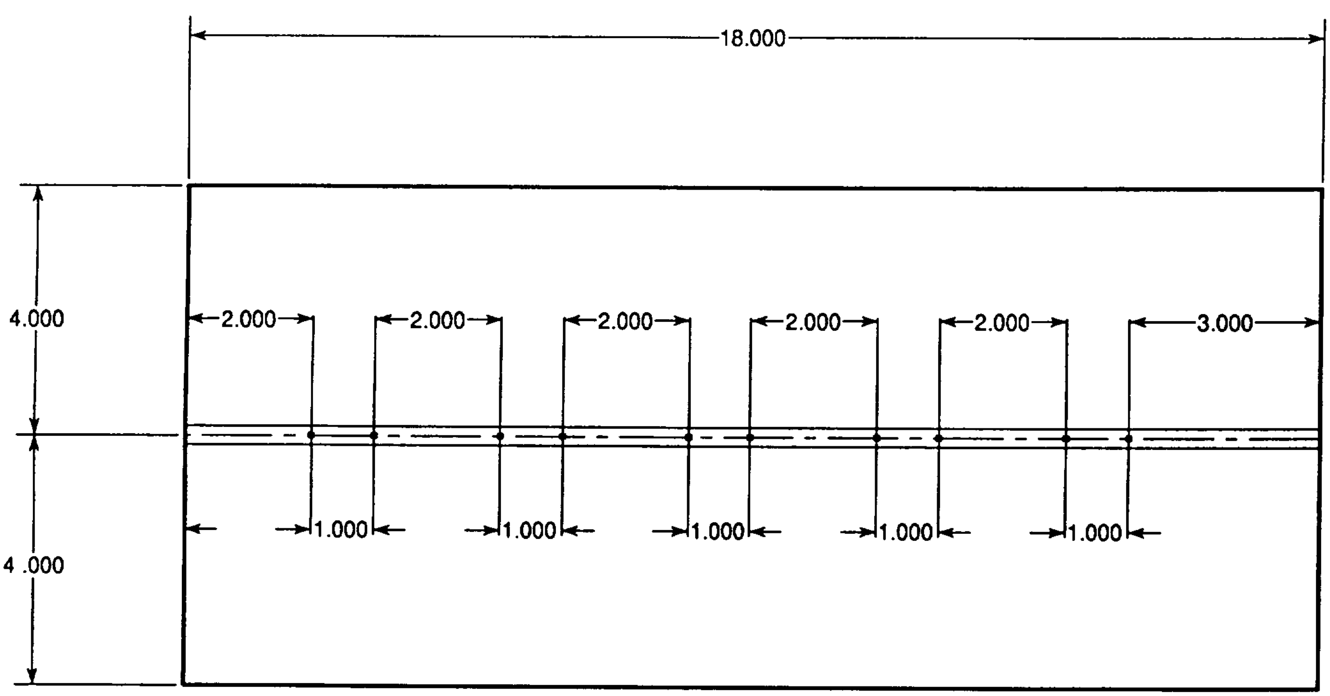


Figure 2. Repair welding panel layout.

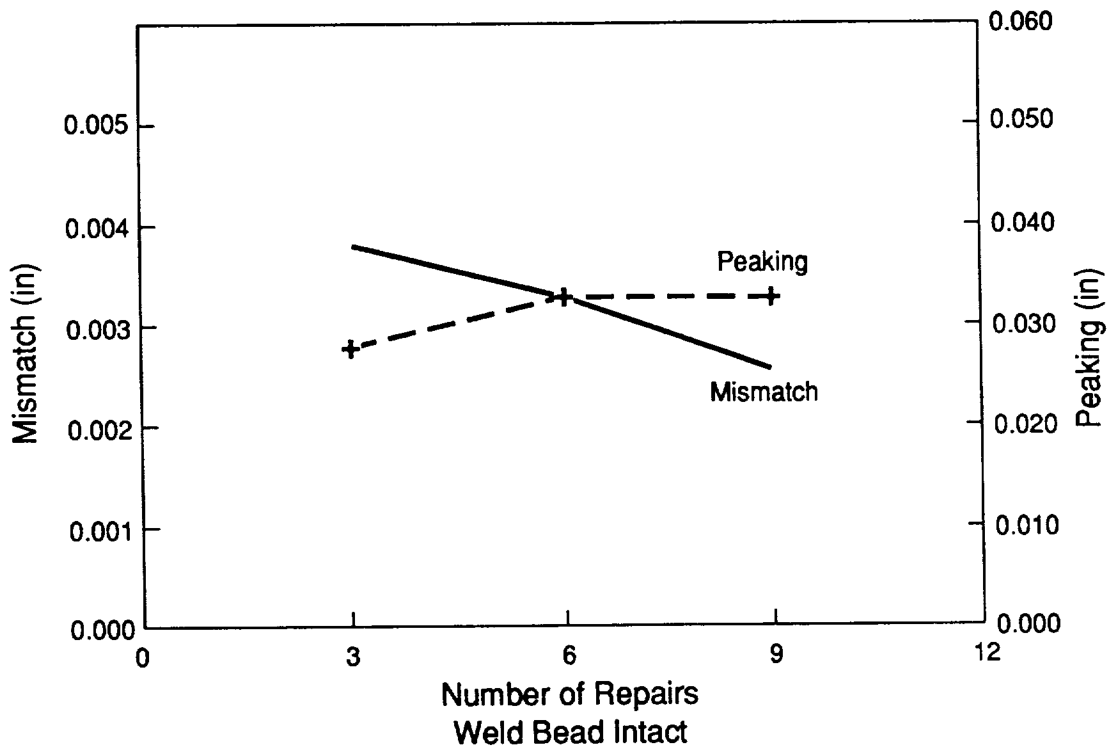


Figure 3. Mean value of peaking and mismatch versus number of repairs (bead intact).

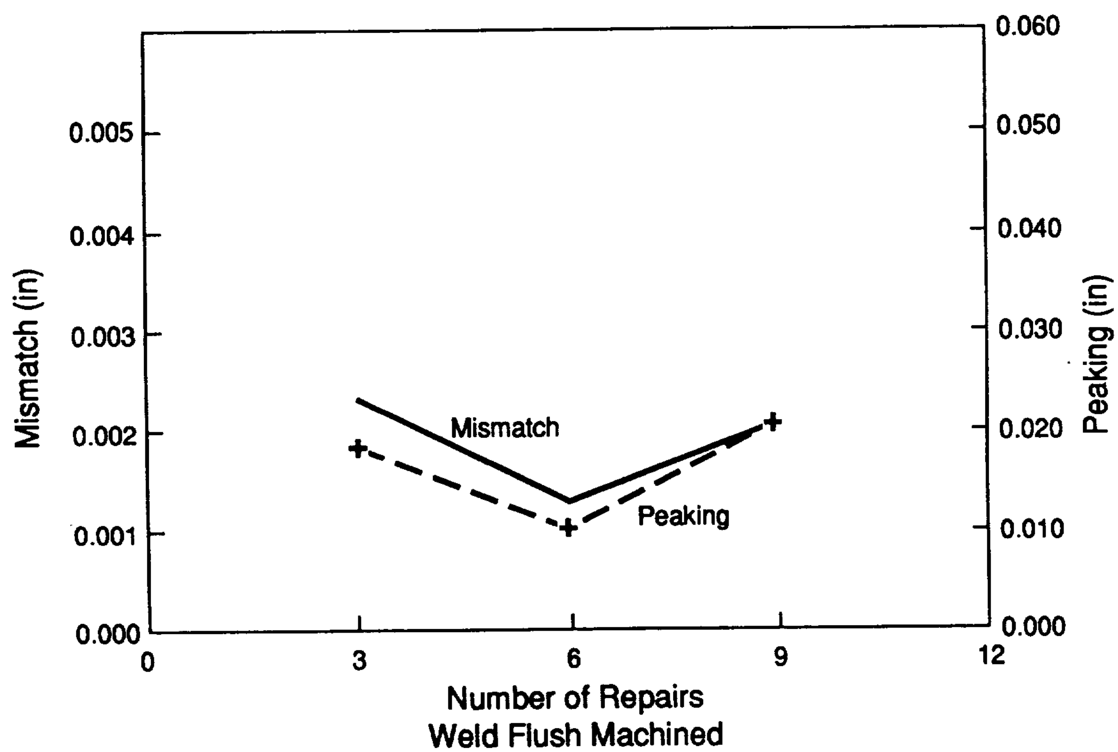


Figure 4. Mean value of peaking and mismatch versus number of repairs (flush machined).

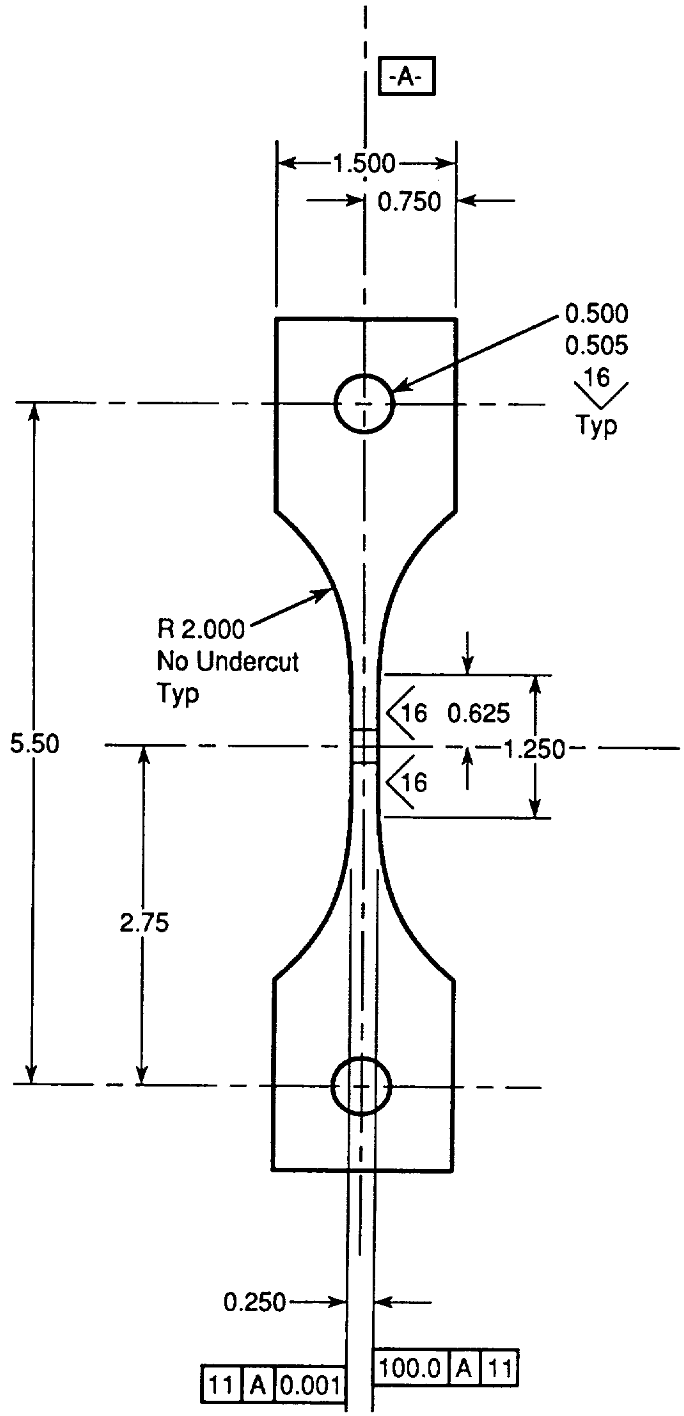


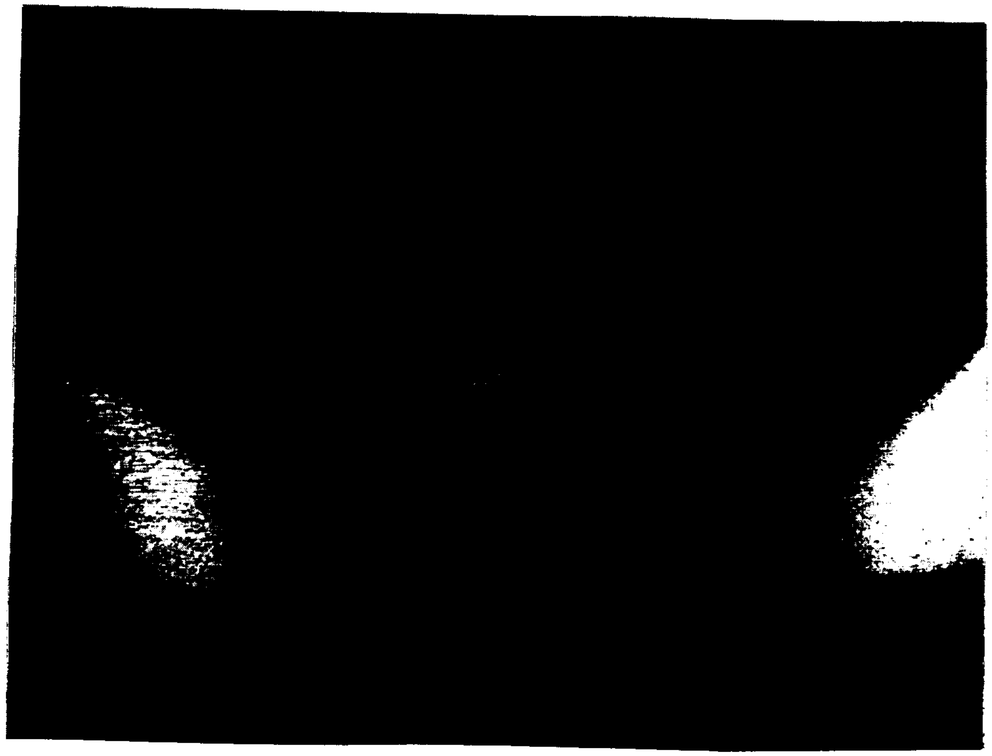
Figure 5. Mechanical test specimen configuration.

10 X

Figure 6. Weld cross section 3 repairs as welded.

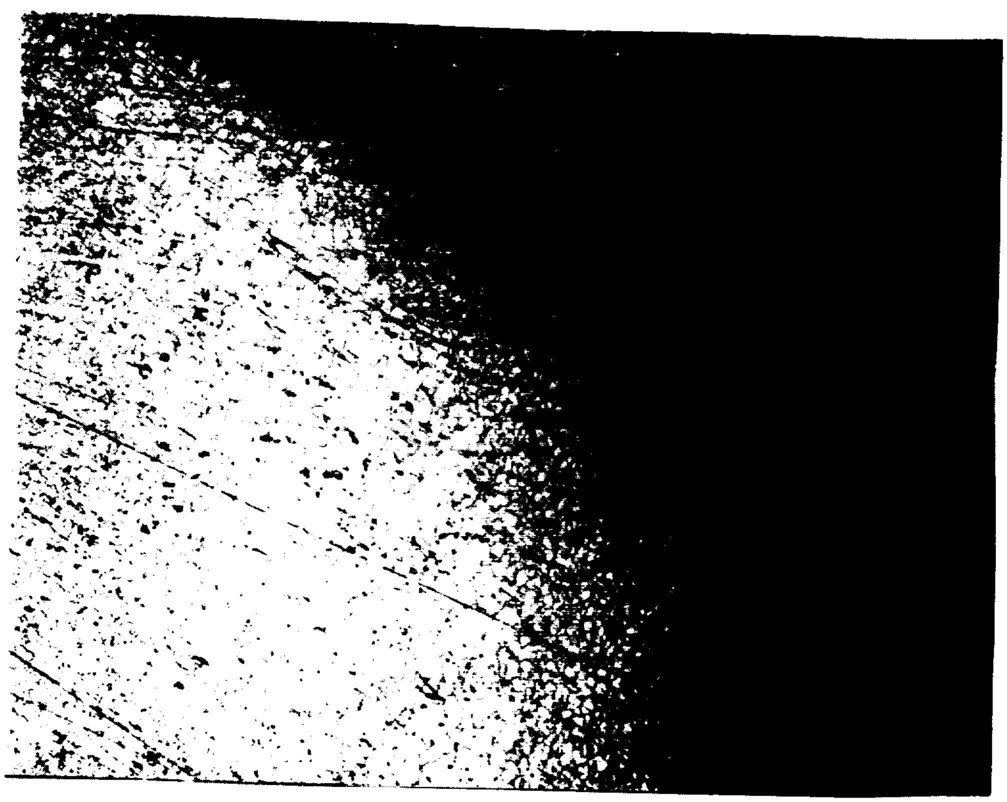
10 X

Figure 7. Weld cross section 6 repairs as welded.



10 X

Figure 8. Weld cross section 9 repairs as welded.

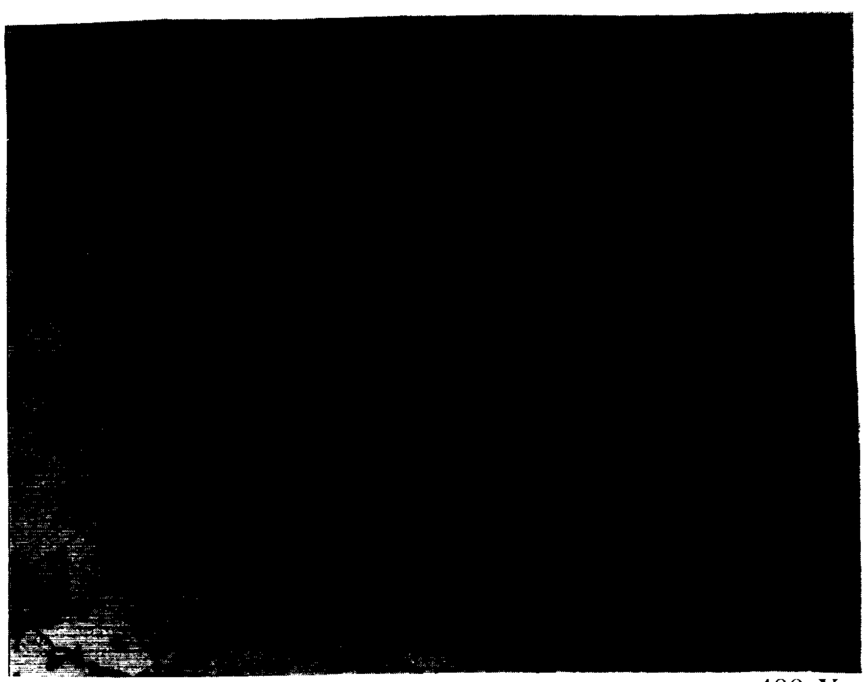


100 X

Figure 9. Heat affected zone 9 repairs, STA1 condition.

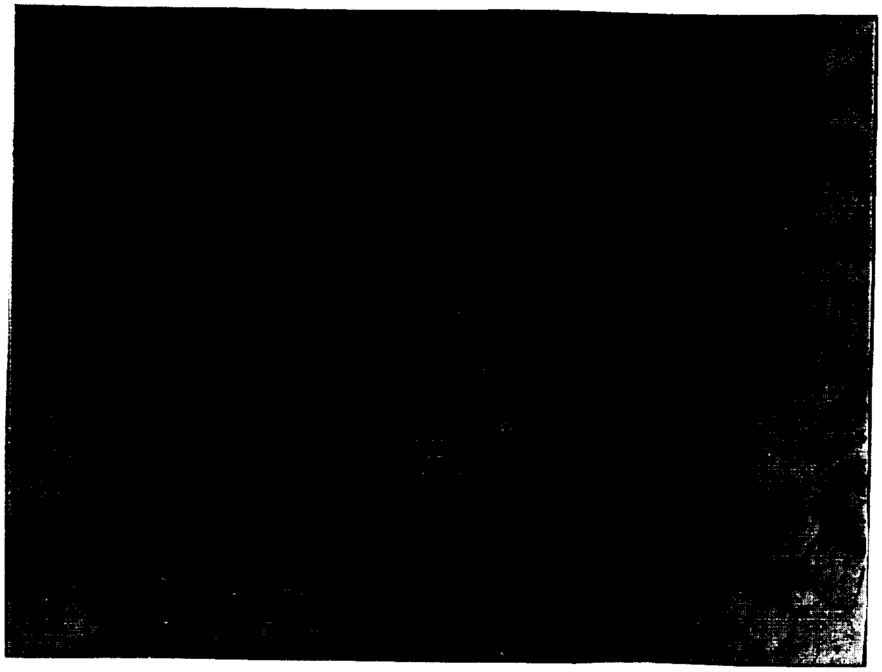
400 X

Figure 10. Fusion zone line no repairs STA1 condition.



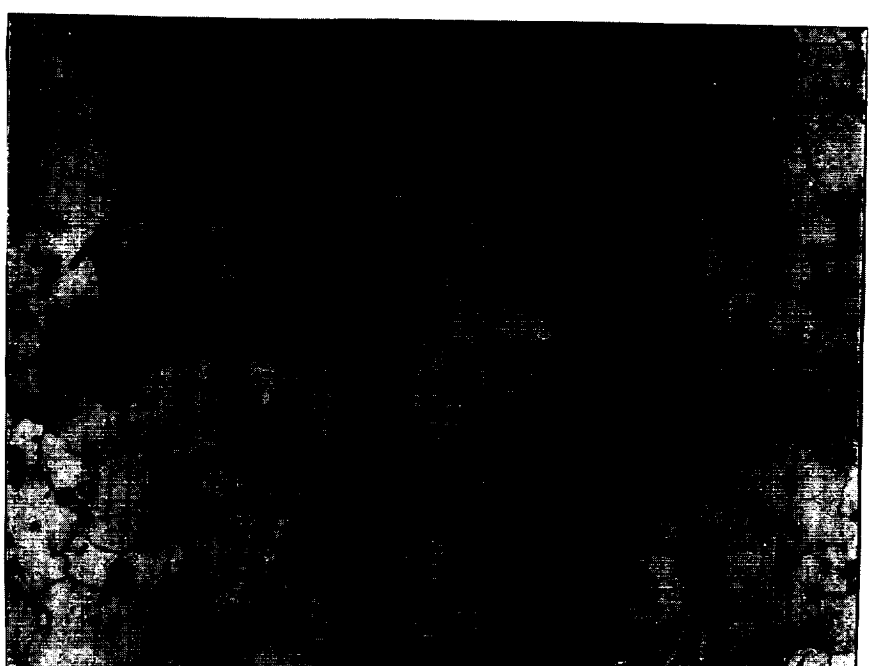
400 X

Figure 11. Fusion zone line 3 repairs STA1 condition.



400 X

Figure 12. Fusion zone line 6 repairs STA1 condition.



400 X

Figure 13. Fusion zone line 9 repairs STA1 condition.

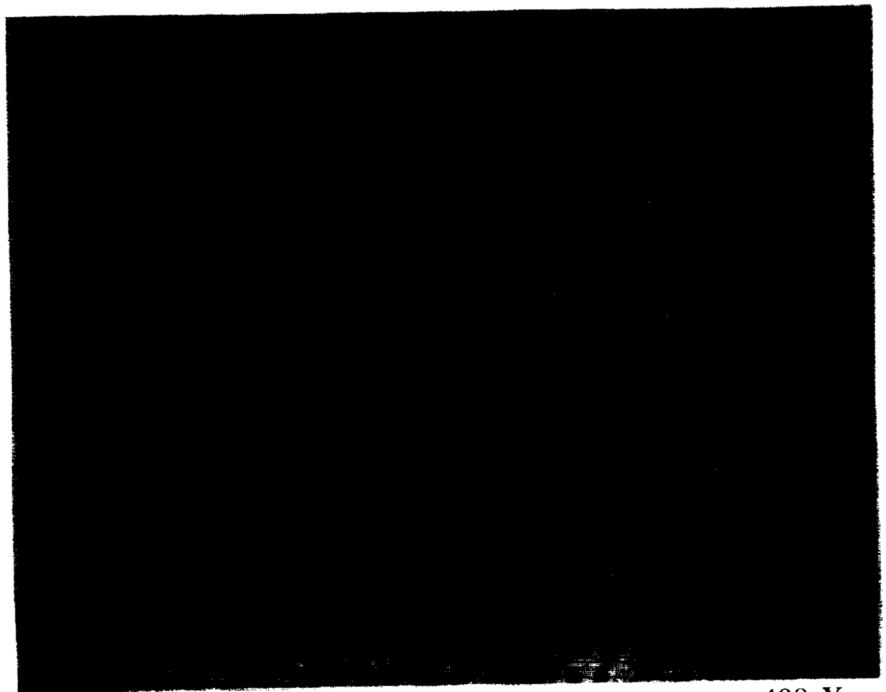


Figure 14. Fusion zone line 9 repairs as welded.

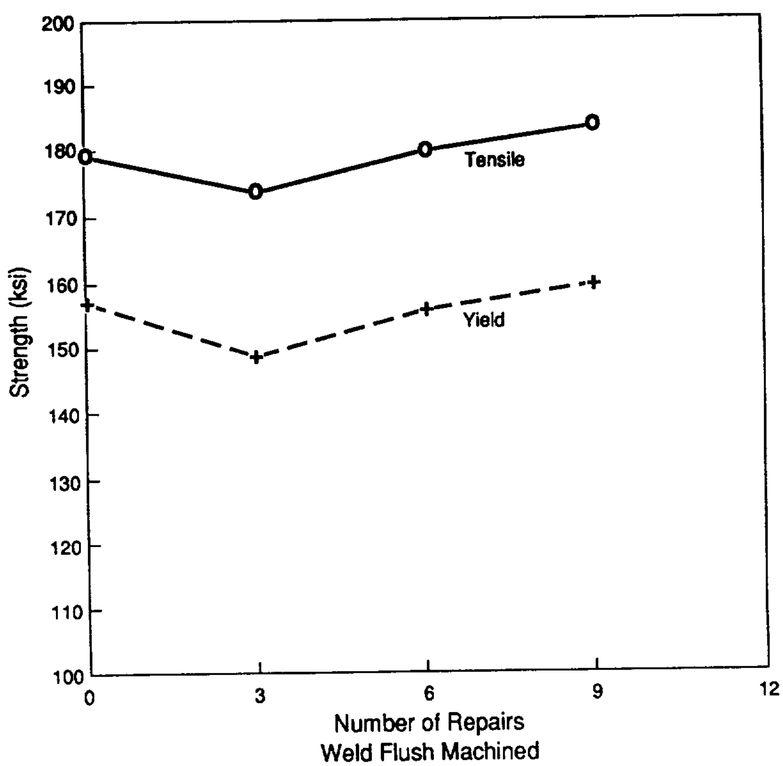


Figure 15. Mean tensile properties versus number of repairs (flush machined).

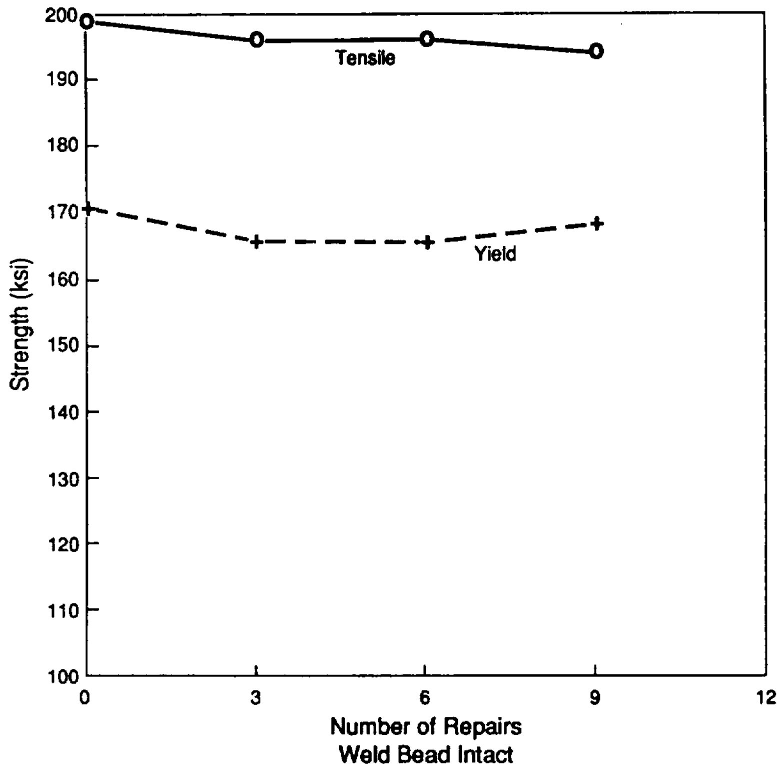


Figure 16. Mean tensile properties versus number of repairs (bead intact).

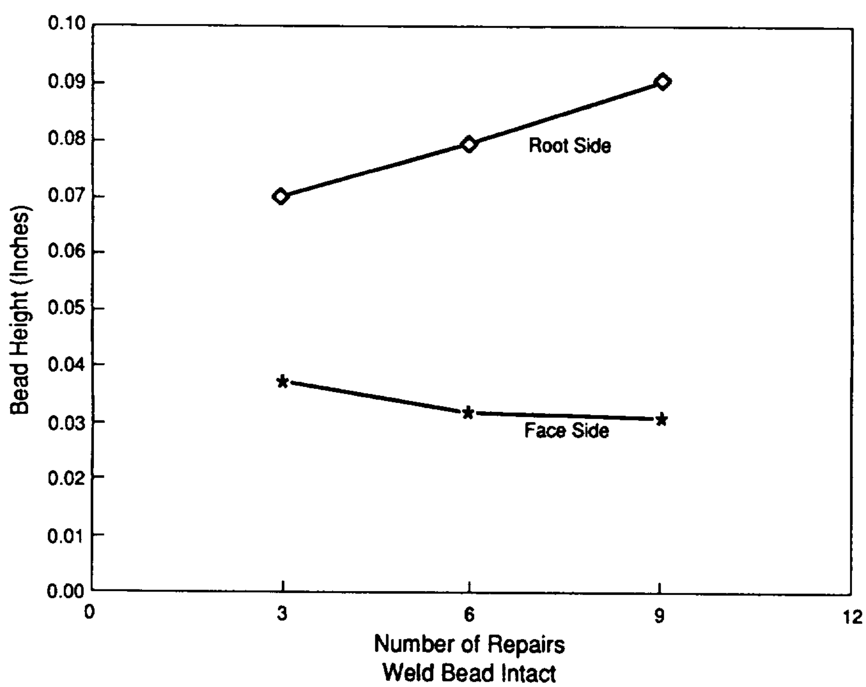


Figure 17. Weld bead profile versus number of repairs.

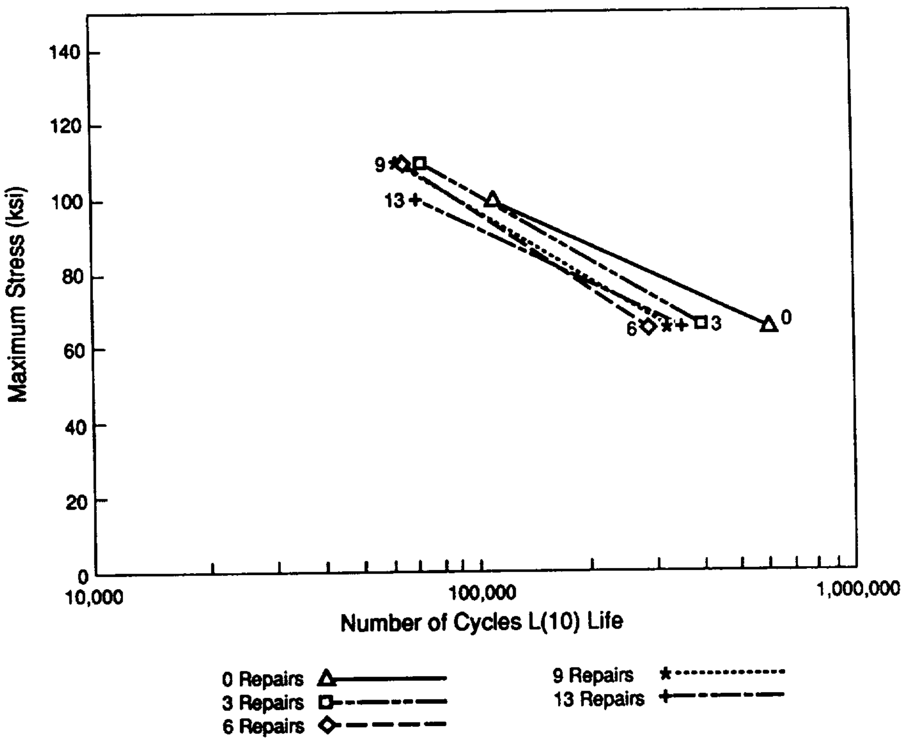


Figure 18. L(10) life for welds flush machined.

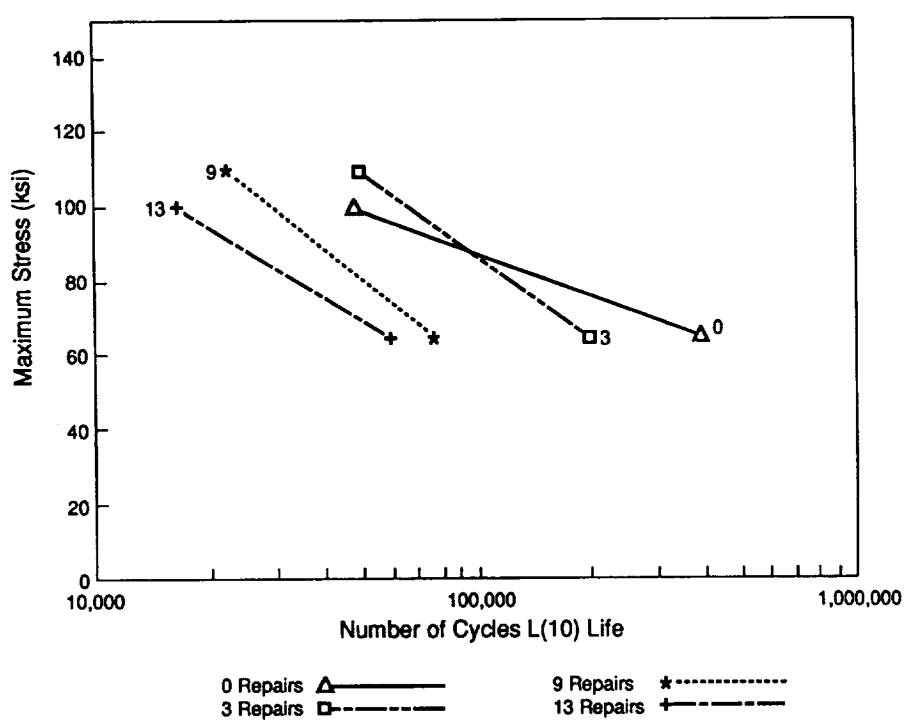
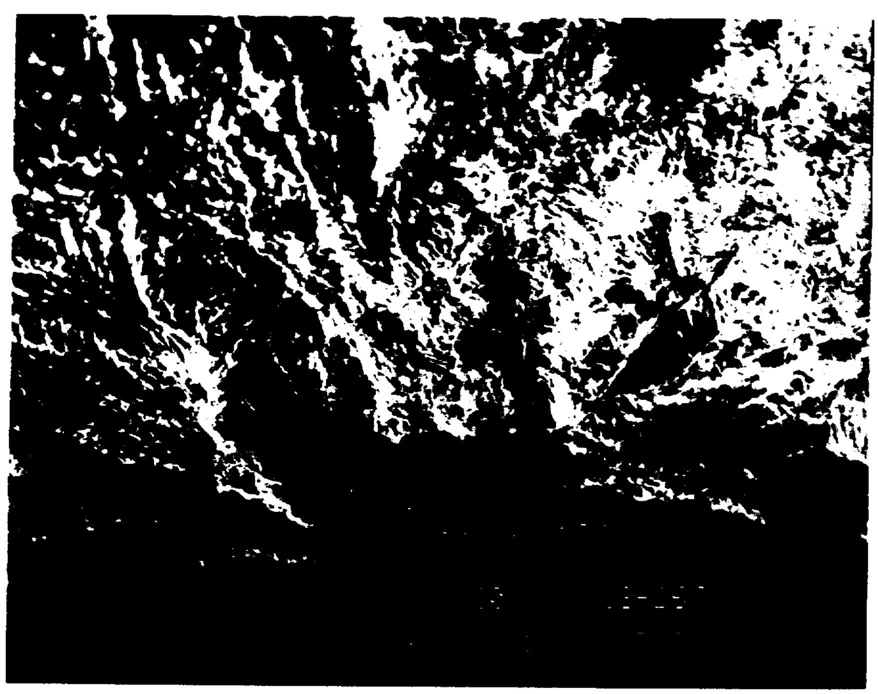


Figure 19. L(10) life for welds bead intact.

(A)



(B)

Figure 20. Fracture surface SEM micrographs unrepaired weld.

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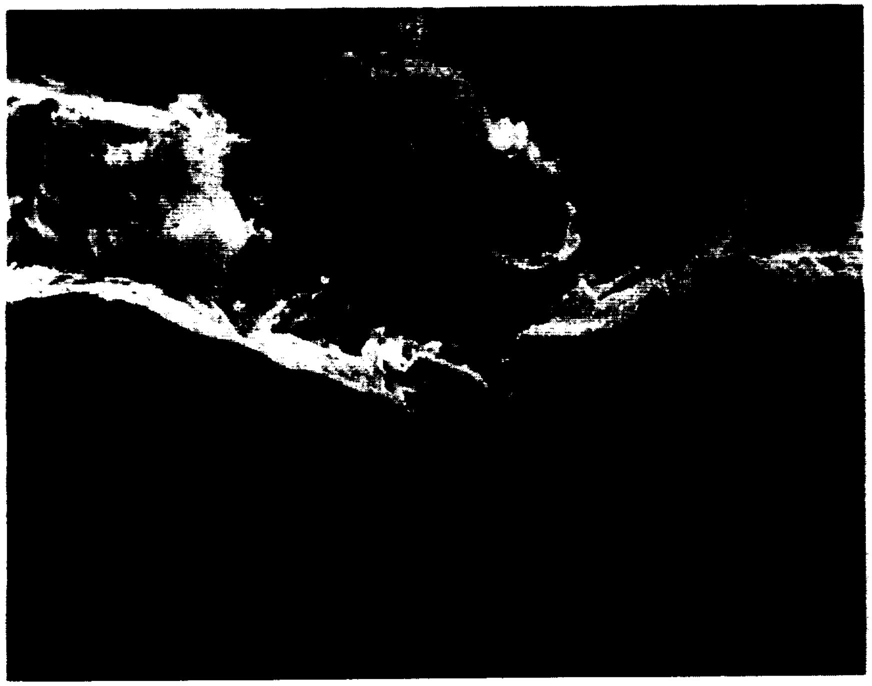
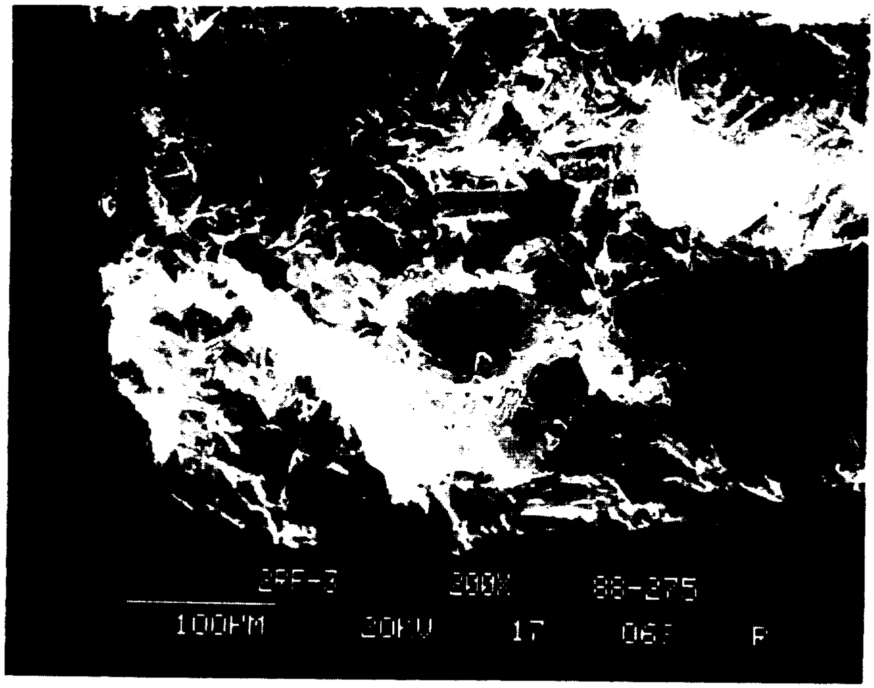


(C)

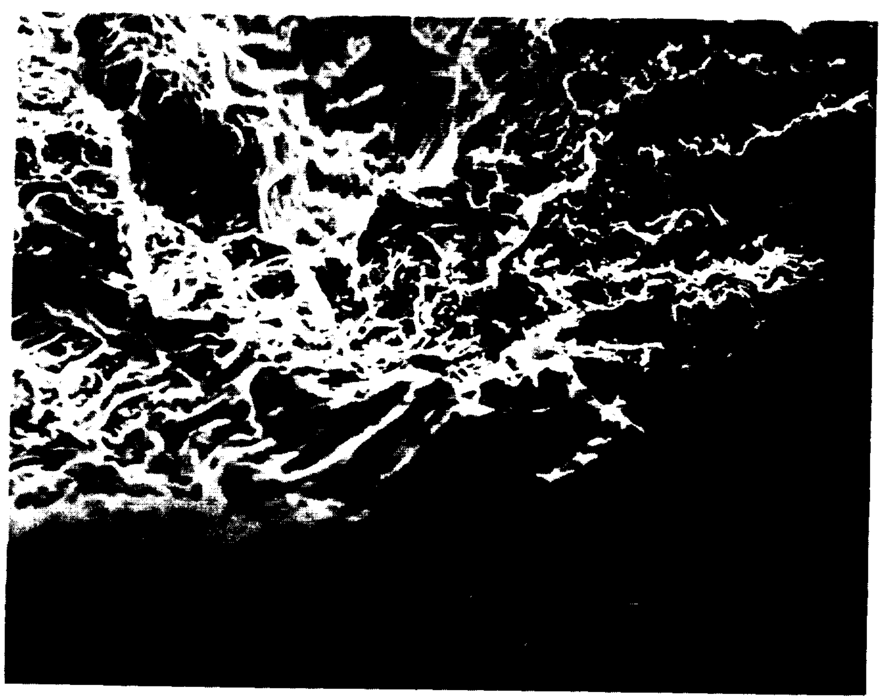
Figure 20. Fracture surface SEM micrographs unrepaired weld (Continued).

(A)

Figure 21. Fracture surface SEM micrographs for 13 repaired welds.



(B)



(C)

Figure 21. Fracture surface SEM micrographs for 13 unrepaired welds (Continued).

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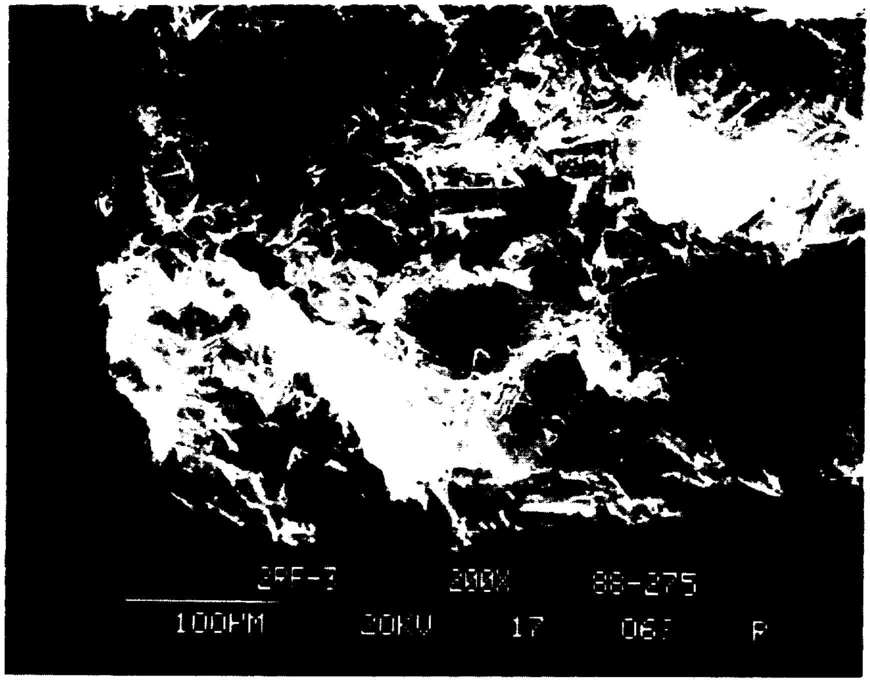
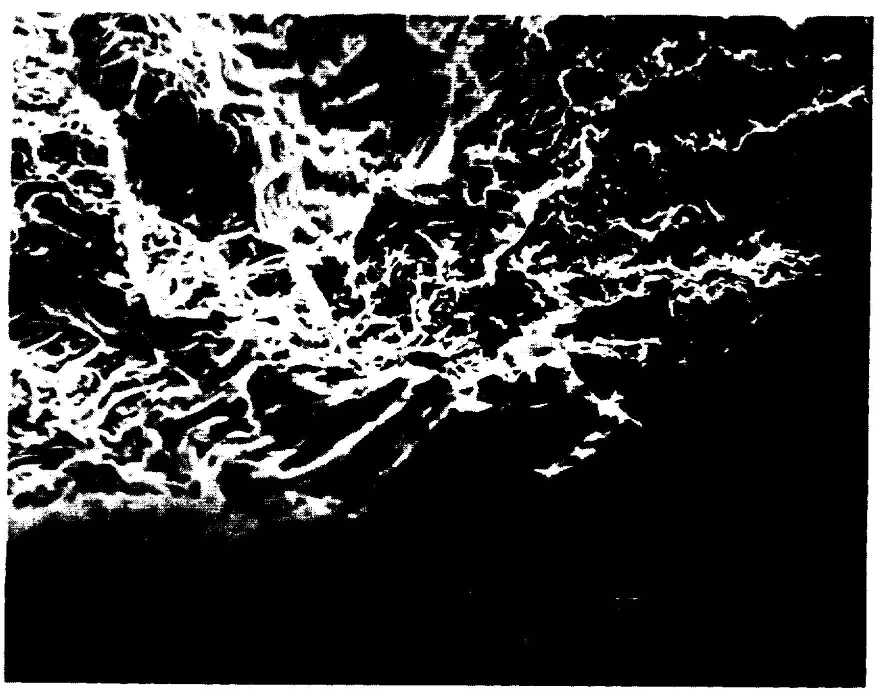


(B)



(C)

Figure 21. Fracture surface SEM micrographs for 13 unrepaired welds (Continued).

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APPROVAL

THE EFFECTS OF MULTIPLE REPAIRS ON INCONEL 718 WELD MECHANICAL PROPERTIES

By C.K. Russell, A.C. Nunes, Jr., and D. Moore

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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